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Analysis of VAWT aerodynamics and design using the Actuator Cylinder flow model

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Outline

- Background
- The Actuator Cylinder flow model
- Results
- Conclusions
- Outlook

Renewed interest in Vertical Axis Wind Turbines

Designs of the 1980´s

Credits Image by Grimshaw & Wind Power Ltd

Recent designs

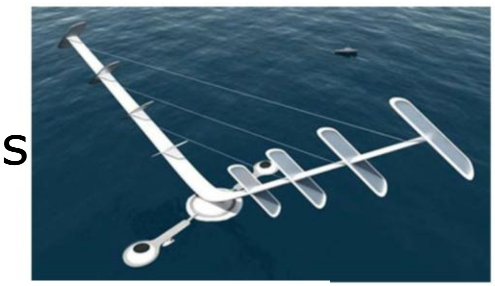


Photo: Grimshaw Architects.

Considered turbine

Accurate aerodynamic and aeroelastic design tools are necessary for the design studies of the new VAWT concepts

Aerodynamic models (Paraschivoiu 2002):

- ❑ Stream tube/momentum models
  - single stream tube (SST) model (Templin 1974)
  - multiple stream tube model (MST) (Strickland 1975)
  - double multiple stream tube (DMST) model (Paraschivioiu 1981)
- ❑ Vortex models
  - fixed wake models
  - free wake models (e.g. Ferreira 2009)
- ❑ CFD models
  - 2D
  - 3D

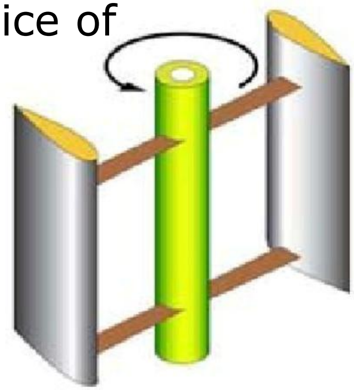
Shortcommings of the stream tube models

- Based on a model (actuator disc) for horizontal axis turbines
- one dimensional
- possible interaction between upstream and downstream rotor part, (DMST) model

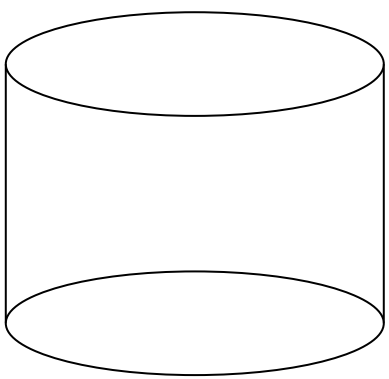
The Actuator Cylinder (AC) flow model

- an extension of the actuator disc AD concept to an actuator cylinder

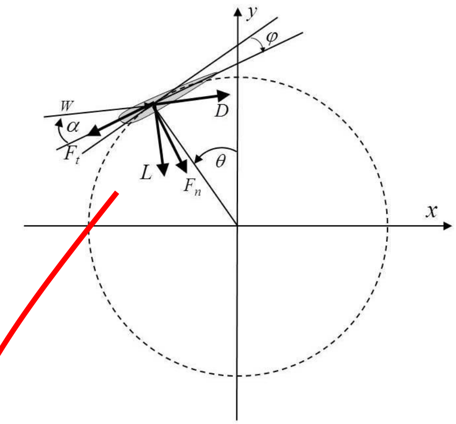
horizontal slice of a VAWT

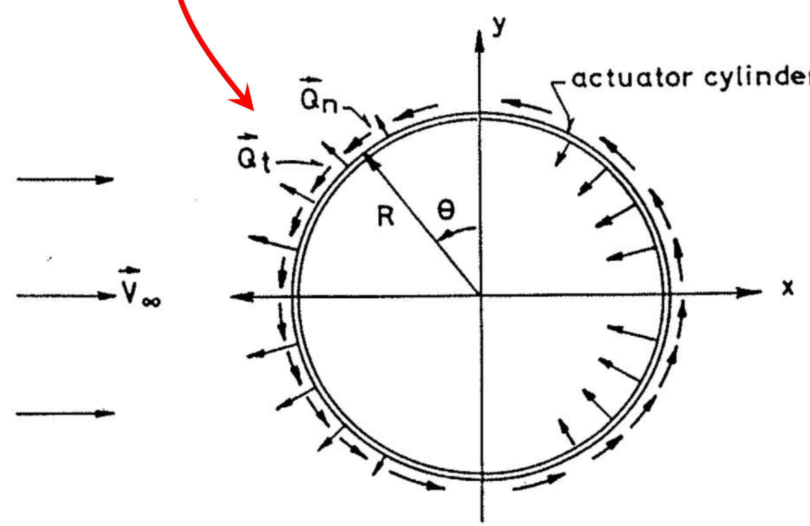


Swept surface a cylinder



The reaction of blade forces distributed on the cylinder surface





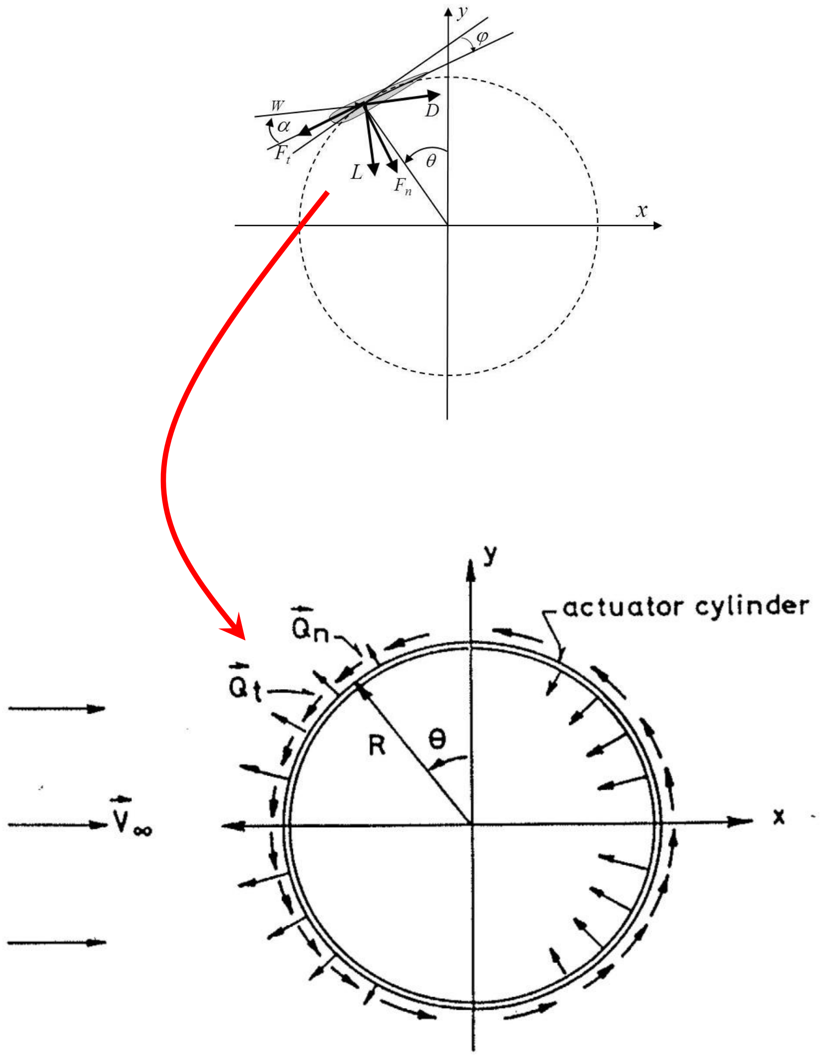
The AC flow model

Blade forces distributed on the cylinder surface:

$$Q_n(\theta) = B\frac{F_n(\theta)\cos(\varphi) - F_t(\theta)\sin(\varphi)}{2\pi R}$$

$$Q_t(\theta) = -B\frac{F_t(\theta)\cos(\varphi) + F_n(\varphi)\cos(\varphi)}{2\pi R}$$

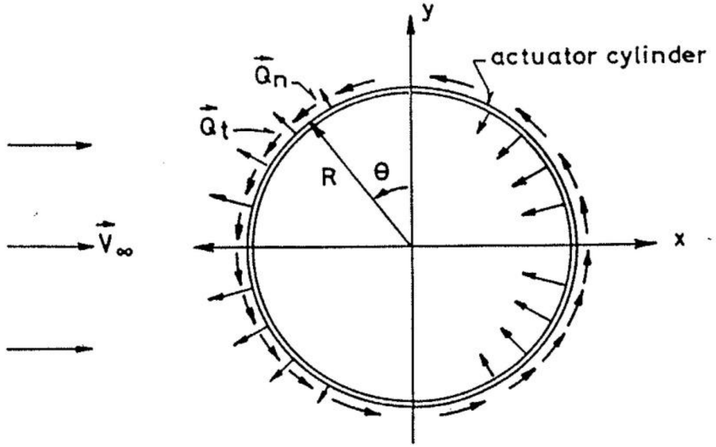
Where $F_n(\theta)$ and $F_t(\theta)$ are the projections of the lift and drag blade forces on a direction normal to chord and tangential to the chord



The ideal energy conversion in a VAWT
- the ideal VAWT

- the normal volume forces $Q_n(\theta)$ not linked to the blade forces but just specified

- the tangential volume forces $Q_t(\theta)$ set to zero. Inviscid flow and infinite tip speed ratio



The converted power is:

$$P_i = \int_0^{2\pi} v_n(\theta) Q_n(\theta) R \, d\theta$$

Power coefficients:

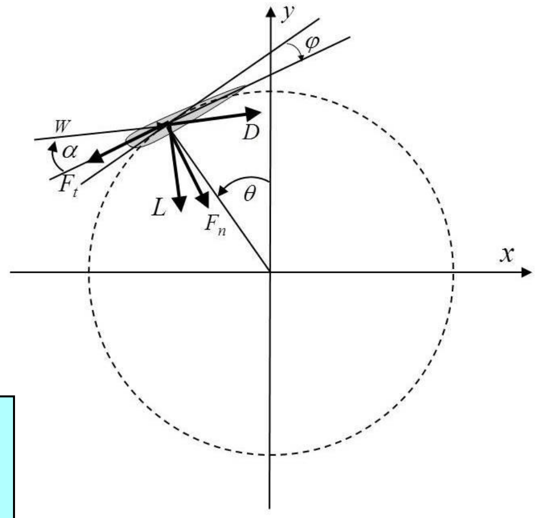
Integral

$$C_{pi} = \frac{P_i}{\frac{1}{2}\rho V_\infty^3 2R} = \frac{\int_0^{2\pi} v_n(\theta) Q_n(\theta) d\theta}{\rho V_\infty^3}$$

Local

$$C_{pi} = \frac{v_n(\theta) Q_n(\theta)}{\rho V_\infty^3}$$

The real energy conversion



$$P = \frac{1}{2\pi}\int_0^{2\pi} B\left(F_t(\theta)\cos(\varphi) + F_n(\theta)\sin(\varphi) \right) R\,\Omega\, d\theta$$

$$C_p = \frac{P}{\frac{1}{2}\rho V_\infty^3\, 2R} = \frac{\frac{1}{2\pi}\int_0^{2\pi} B\left(F_t(\theta)\cos(\varphi) + F_n(\theta)\sin(\varphi) \right)\Omega\, d\theta}{\rho V_\infty^3}$$

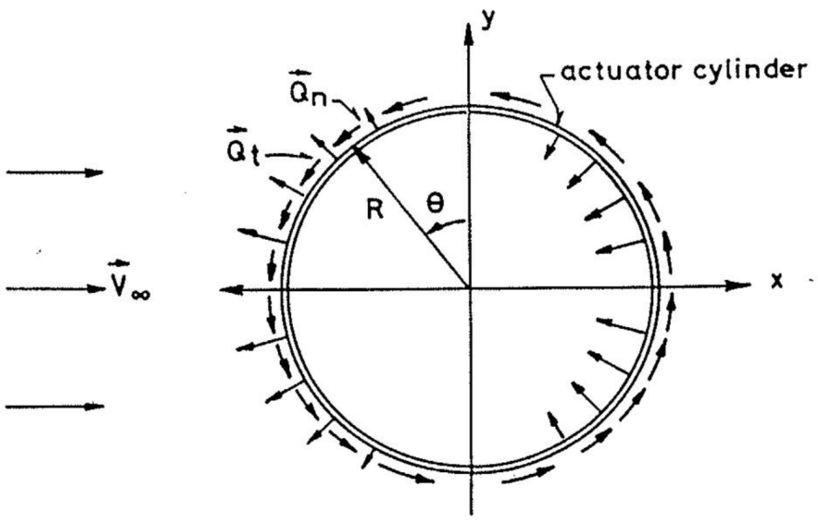
$$C_T = \frac{\int_0^{2\pi}\left(Q_n(\theta)\sin(\theta) + Q_t(\theta)\cos(\theta)\right) R\, d\theta}{\frac{1}{2}\rho V_\infty^2\; 2R} = \frac{\int_0^{2\pi}\left(Q_n(\theta)\sin(\theta) + Q_t(\theta)\cos(\theta) \right) d\theta}{\rho V_\infty^2}$$

Describing equations and method of solution - a 2D version

1) a standard CFD code can be used:

$$Q_n(\theta) = \int_{-\Delta s}^{\Delta s} f_n(\theta)\,dr$$

$$Q_t(\theta) = \int_{-\Delta s}^{\Delta s} f_t(\theta)\,dr$$



2) a solution procedure with potentials for low computational demands:

Approach: solution is split into a linear and a non-linear part

Velocity components are written as:

$$v_x = 1 + w_x \quad and \quad v_y = w_y$$

Equations non-dimensionalized with: V_∞, ρ, R

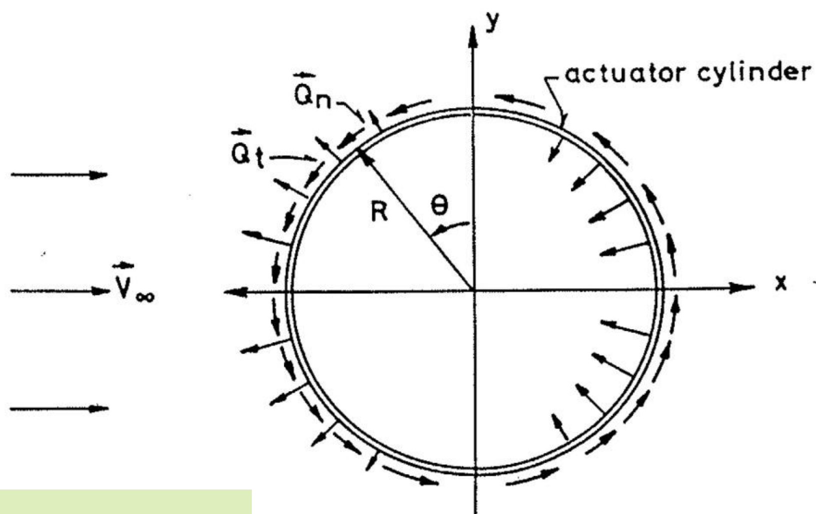
Describing equations and method of solution - a 2D version – cont´d

Equations: 2D Euler + eq. of continuity

$$\frac{\partial w_x}{\partial x} + w_x \frac{\partial w_x}{\partial x} + w_y \frac{\partial w_x}{\partial y} = -\frac{\partial p}{\partial x} + f_x$$

$$\frac{\partial w_y}{\partial x} + w_x \frac{\partial w_y}{\partial x} + w_y \frac{\partial w_y}{\partial y} = -\frac{\partial p}{\partial y} + f_y$$

$$\frac{\partial w_x}{\partial x} + \frac{\partial w_y}{\partial y} = 0$$



$$\frac{\partial w_x}{\partial x} = -\frac{\partial p}{\partial x} + f_x + g_x$$

$$\frac{\partial w_y}{\partial x} = -\frac{\partial p}{\partial y} + f_y + g_y$$

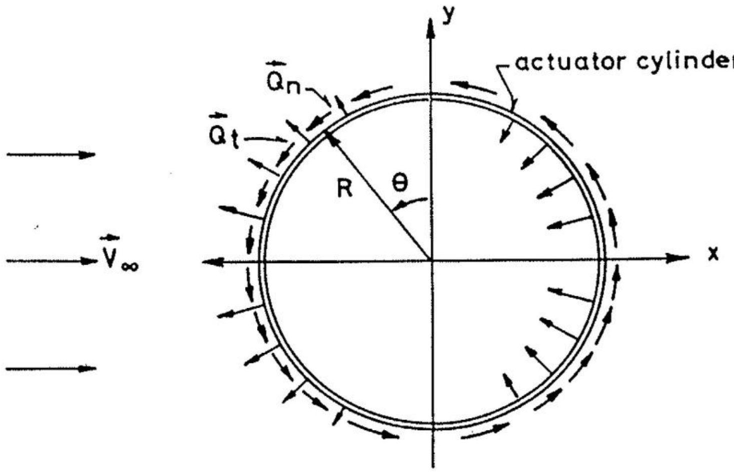
$$g_x = -\left(w_x \frac{\partial w_x}{\partial x} + w_y \frac{\partial w_x}{\partial y} \right)$$

$$g_y = -\left(w_x \frac{\partial w_y}{\partial x} + w_y \frac{\partial w_y}{\partial y} \right)$$

Describing equations and method of solution - a 2D version – cont´d

The following Poisson type equation can now be derived for the pressure:

$$\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}=\left(\frac{\partial f_x}{\partial x}+\frac{\partial f_y}{\partial y}\right)+\left(\frac{\partial g_x}{\partial x}+\frac{\partial g_y}{\partial y}\right)$$



Final solution can be derived as a sum of a linear and non-linear part

$$w_x = w_x(f)+w_x(g) \quad and \quad w_y = w_y(f)+w_y(g)$$

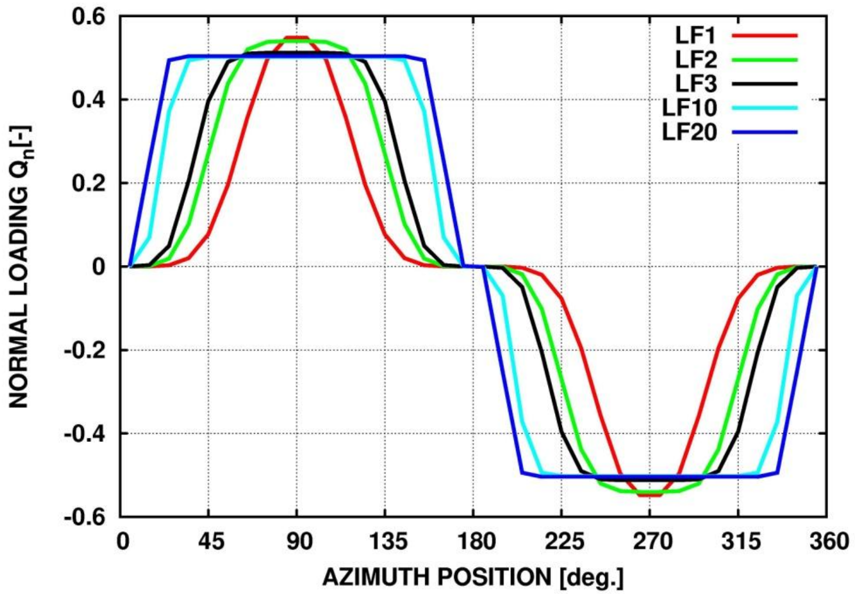
The velocities from the linear solution:

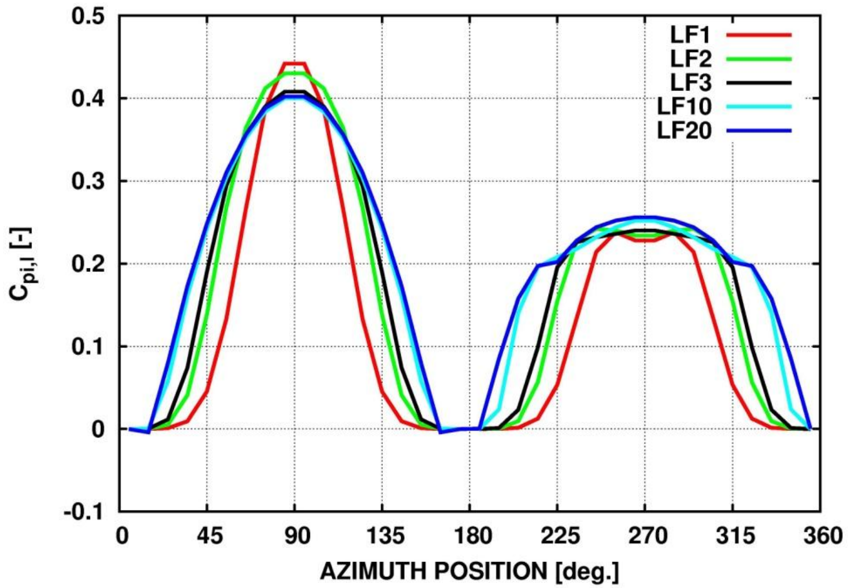
$$w_x=-\frac{1}{2\pi}\int_0^{2\pi} Q_n(\theta)\frac{-x(x+\sin(\theta))\sin(\theta)+(y-\cos(\theta))\cos(\theta)}{(x+\sin(\theta))^2+(y-\cos(\theta))^2}d\theta - Q_n(\arccos(y))^{*}+Q_n(-\arccos(y))^{**}$$

$$w_y=-\frac{1}{2\pi}\int_0^{2\pi} Q_n(\theta)\frac{-x(x+\sin(\theta))\cos(\theta)-(y-\cos(\theta))\sin(\theta)}{(x+\sin(\theta))^2+(y-\cos(\theta))^2}d\theta$$

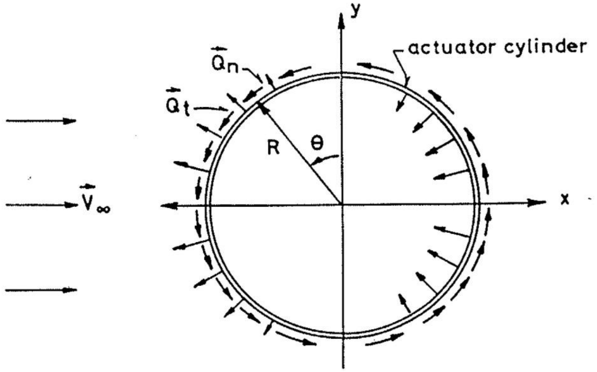
Results

- The optimal loading for maximum C_{pi} ?



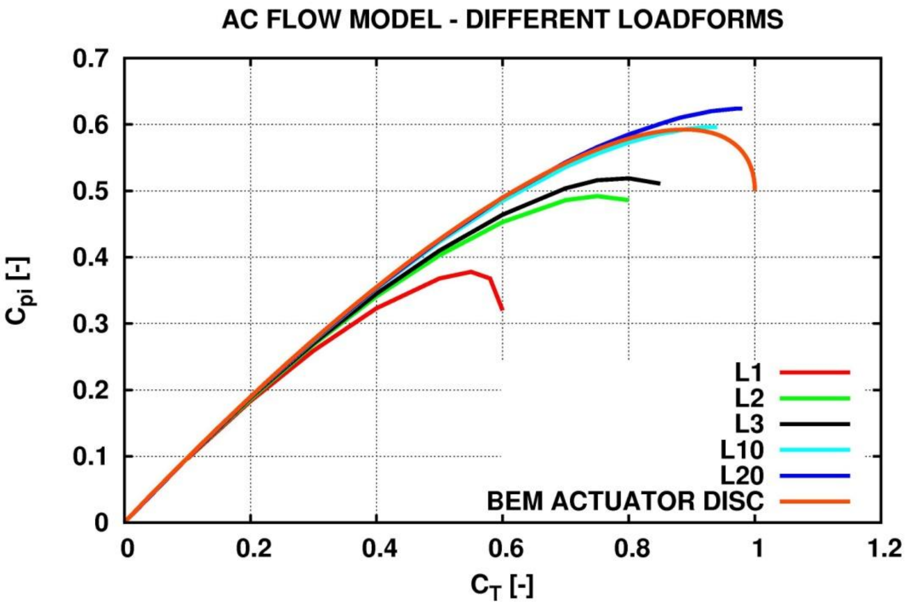


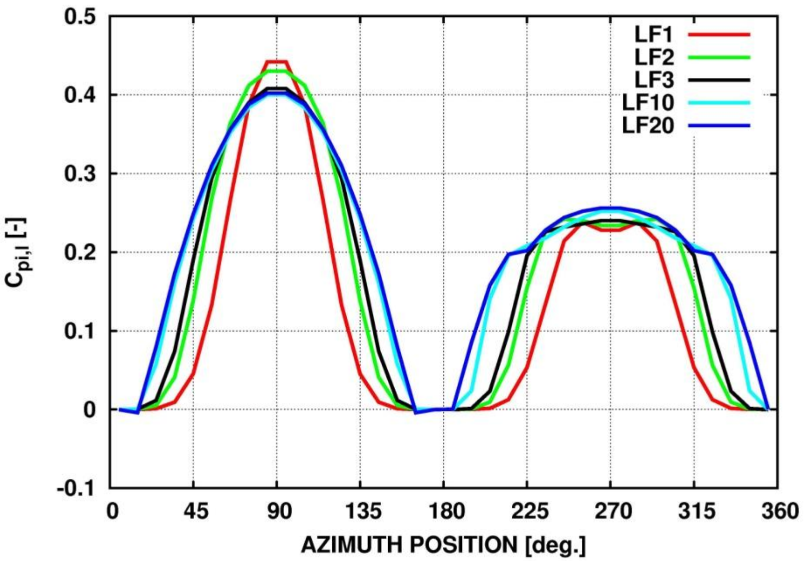
$$Q_n(\theta) = Q_{n,\max} \frac{\sin(\theta)}{|\sin(\theta)|}\left(1 - |\cos(\theta)|^m + \frac{1}{2\pi}\sin\left(2\pi|\cos(\theta)|^m\right)\right)$$



Parameters: $Q_{n,\max}$ *and* m

Results
- The maximum C_{pi} ?

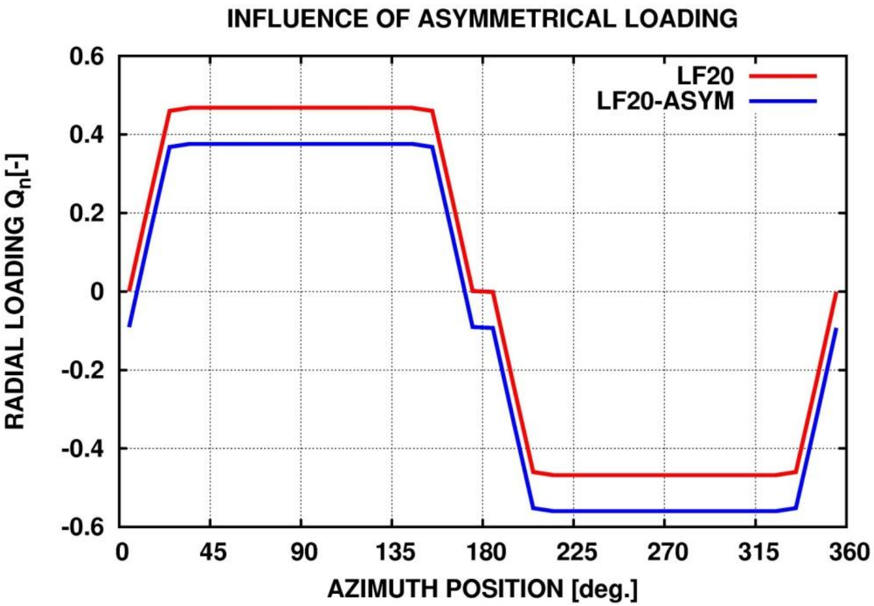




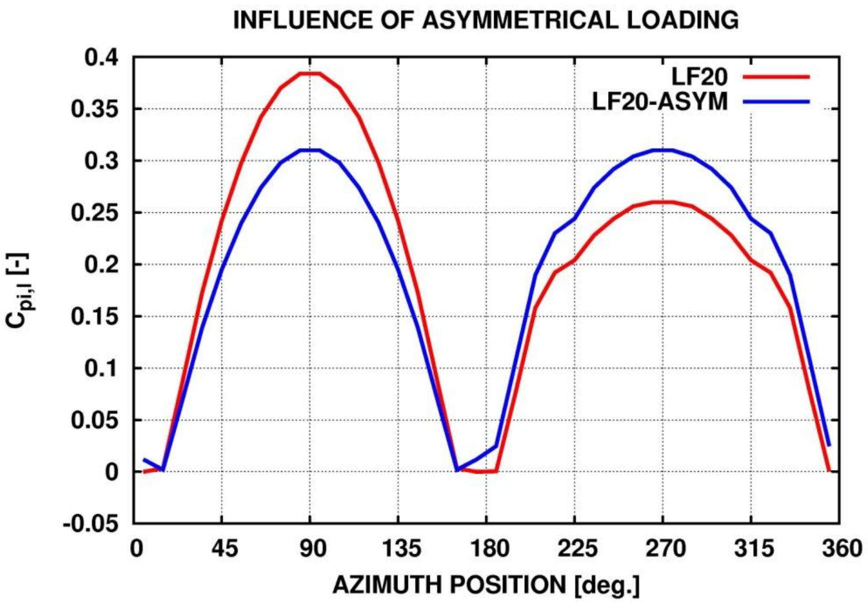
Results

- Asymmetrical loading ?

Loading



Local power coefficient $C_{pi,l}$



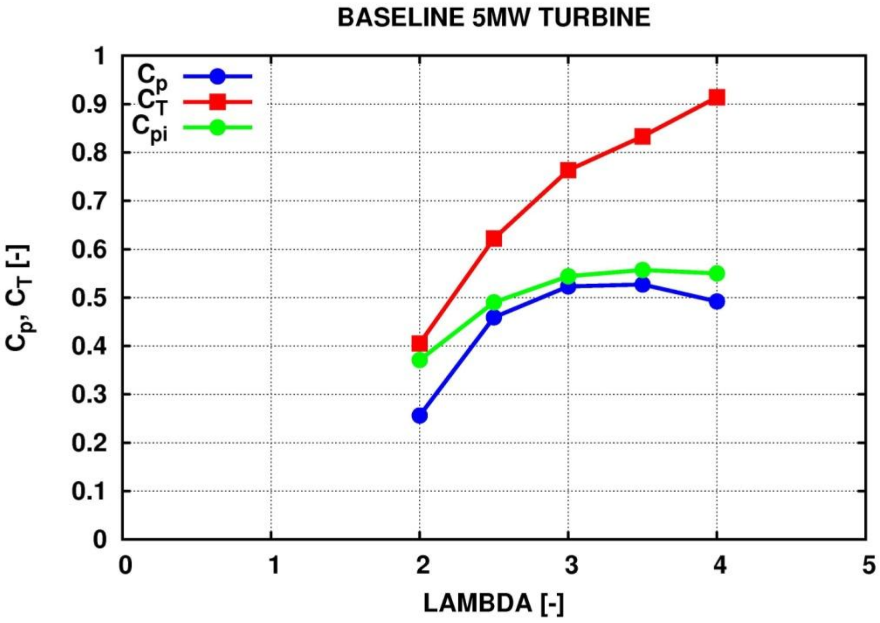
Result: $C_p = 0.63$ for both loadforms

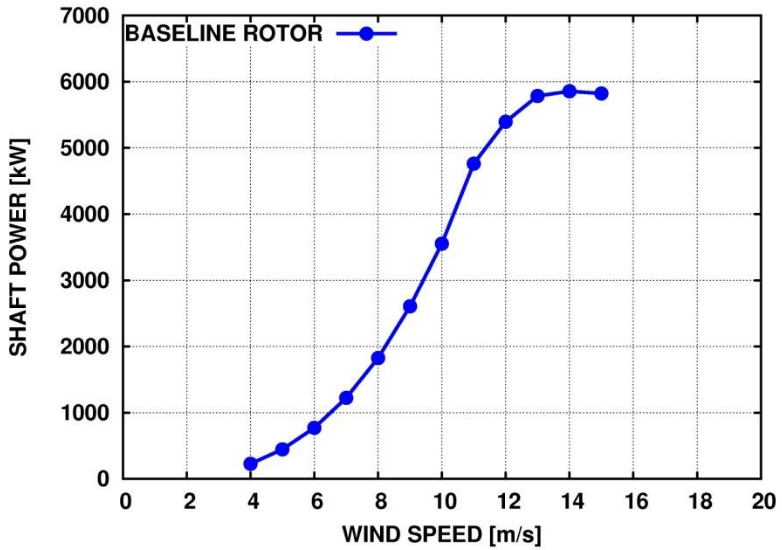
Results
- 5MW baseline DeepWind design -

rotor radius	63.74m
blade chord	7.45m
airfoil	NACA0018
number of blades	2
solidity	0.23
rated power	5000kW
rated speed	5.26rpm
swept area	10743m2
rotor height	84.27m (cylindrical rotor)

Results

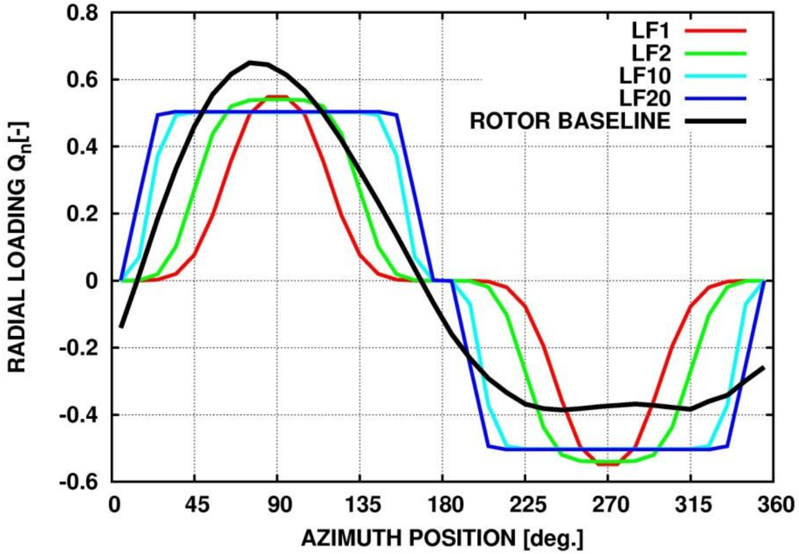
-5MW baseline DeepWind design

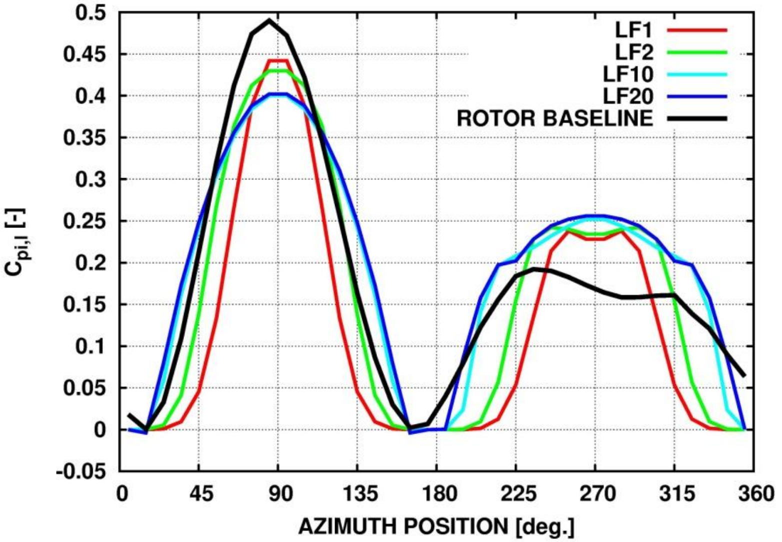




Results

- Actual rotor loading compared with previous investigated loadings
-

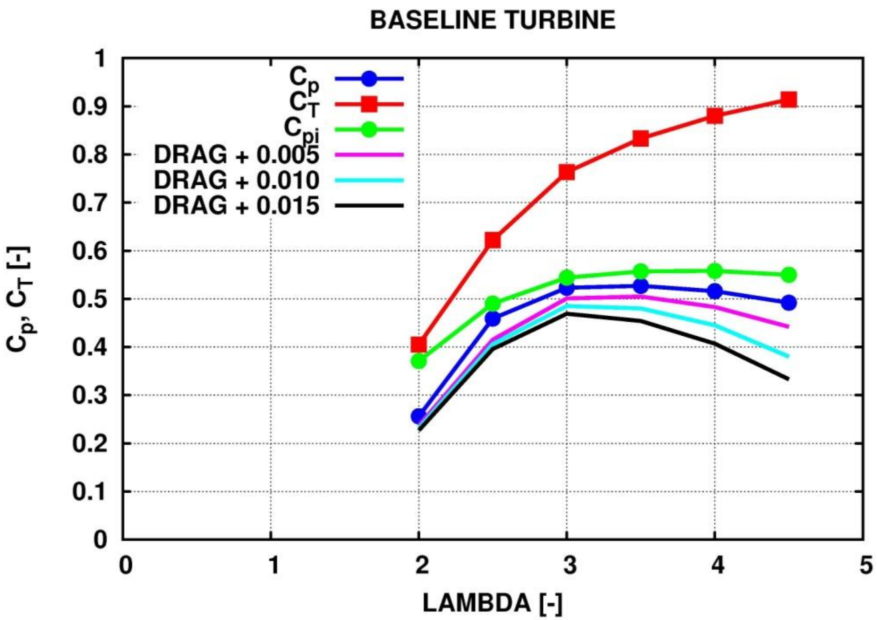


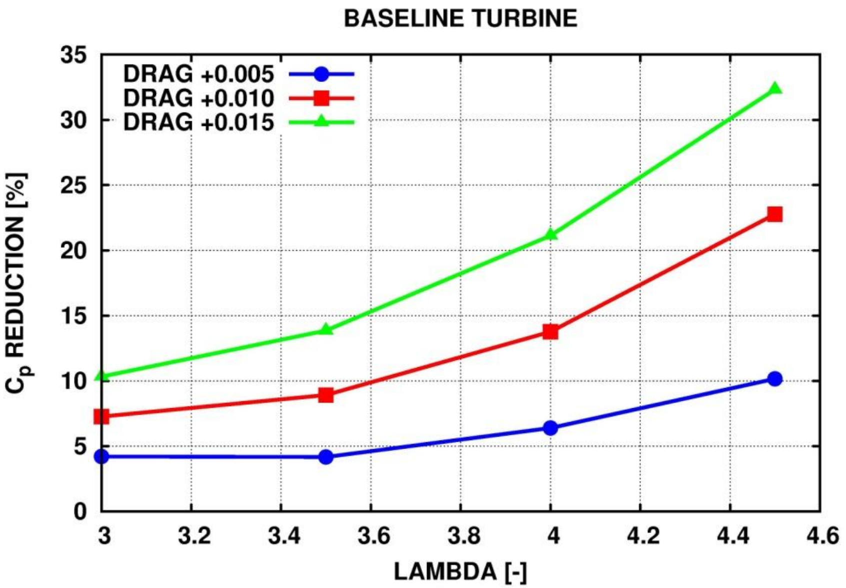


Flaps on the blades could be used to achieve a more optimal loading and thus higher power coefficient

Results

-Influence of additional drag e.g. from struts –



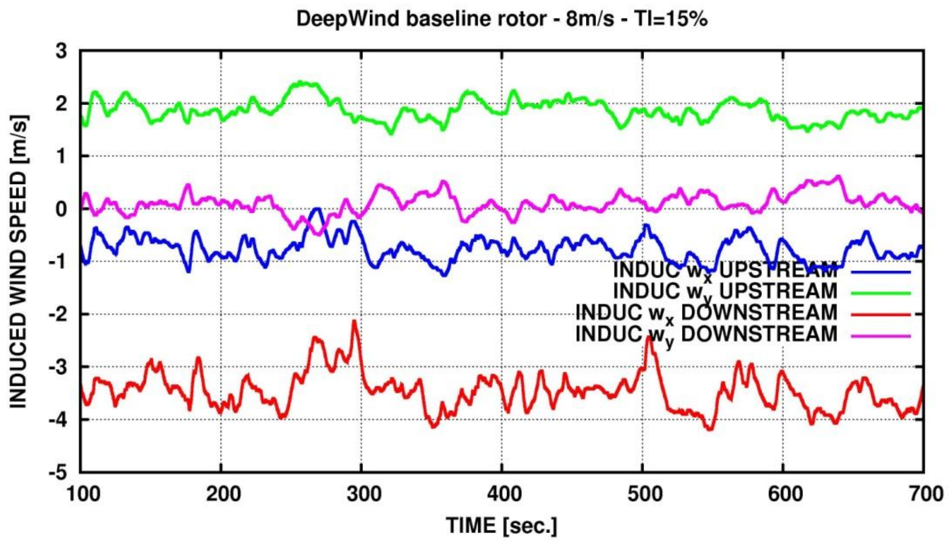


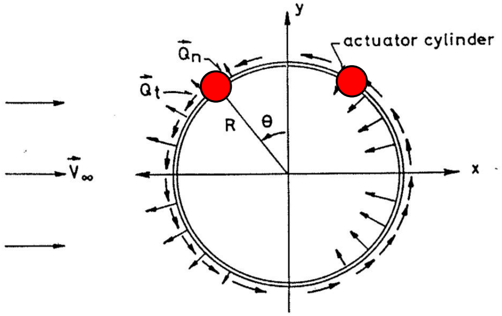
Conclusions

- the AC flow model can be used to study the **ideal** as well as **real** energy conversion of a VAWT
- for a fixed pitch VAWT the loading is not optimal – can be modified e.g. with trailing edge flaps
- the AC flow model can be used for aerodynamic and aeroelastic simulation of VAWT´s

Outlook

- ❑ The AC model has been implemented in the aeroelastic code HAWC2*





❑ Detailed aerodynamic and aeroelastic design of the DeepWind rotor with HAWC2 and the AC model
❑ Comparison with the free wake model of TU Delft (Carlos Ferreira)
❑ Further investigation of the max. C_{pi}

* To be presented at AIAA 2013 in January "Implementation of the Actuator Cylinder flow model in HAWC2 for aeroelastic simulations on Vertical Axis Wind Turbines"

Acknowledgement

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Thank you